Magnetic-Field-Induced Localization Transition in HgCdTe

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We have performed magnetoresistance and Hall-resistance measurements on low-carrier-concentration n-type samples of $Hg_{0.76}Cd_{0.24}Te$ at millikelvin temperatures. We observe an abrupt rise in the Hall resistance and magnetoresistance at a characteristic field H_c which is a significant function of temperature and which allows us to reject magnetic freezeout or localization by disorder as possible mechanisms. We believe our data provide compelling evidence for a model where the magnetic field induces localization of the electrons into a three-dimensional Wigner lattice.

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Since Wigner introduced the notion[1] in 1934, the concept of an electron lattice has been a compelling one. In an elegant experiment,[2] Grimes and Adams demonstrated that a monolayer of electrons could be frozen into a periodic crystalline array on the surface of liquid helium. More recently, magnetoresistance anomalies[3] in graphite suggested the possibility of an electron crystal, but the data seem to be best described[4] by a one-dimensional charge-density-wave instability along the magnetic field direction. We report here what we believe to be the first unambiguous demonstration of a three-dimensional Wigner crystal, deduced from magnetoresistance and Hall measurements on $Hg_{1-x}Cd_xTe$ at millikelvin temperatures.

The high mobility of $Hg_{1-x}Cd_xTe$ compounds at a low-carrier density allows the extreme quantum limit to be reached at magnetic fields of only a few kilo-oersteds and makes them attractive candidates for studying Wigner crystallization. Historically, magneto-transport measurements on $Hg_{1-x}Cd_xTe$ and the related narrow-gap semiconductor InSb have been hotly contested. They have been variously interpreted as evidence for a magnetic-field-induced Mott transition,[5] electron localization into a charge-density wave or a Wigner lattice,[6,7] or magnetic freezeout of the free carriers.[8-10] Our data are more amenable to unequivocal analysis because of the two orders of magnitude lower measuring temperatures and the higher quality samples.

Oriented single crystals of $Hg_{1-x}Cd_xTe$ were grown at Honeywell by a new process referred to as the DME technique.[11] This seeded bulk-crystal growth method enables significant improvements over conventional techniques in the areas of crystallinity, purity, compositional uniformity, precipitate density, and reproducibility. We chose a metallic n-type sample with a carrier density of 1.40×10^{14} cm^{-3}, and a mobility of 1.5×10^5 cm^2/V·sec as determined from Hall measurements at temperature $T=77$ K. The alloy composition $x=0.2378$ varied by only 0.0015 across a 15-mm-diam wafer. Leads were indium soldered to samples of typical dimensions $1.5\times0.8\times0.2$ mm^3, which were then cooled to $T=10$ mK in a top-loading dilution refrigerator. A germanium thermometer was calibrated below 80 mK by measurement of the anisotropy of cobalt-60 decays. Conventional four-wire resistance and Hall measurements were made with use of a lock-in technique at 16 Hz. Input power was confined to less than 10^{-13} W, and all results were in the Ohmic regime.

Narrow-gap semiconductors such as $Hg_{1-x}Cd_xTe$ are good materials in which to study localization in magnetic fields on account of their small conduction-band effective masses m^* and high dielectric constants ϵ_∞. For $x=0.24$, we have $m/m^*\simeq80$ and $\epsilon_\infty\simeq20$. Because the Landau-level splitting $\hbar\omega_c=\hbar eH/m^*c$ is quite large and the carrier density very low, the extreme quantum limit where the electrons are confined to the lowest spin-polarized Landau level can be reached at modest magnetic fields. For this sample, we calculate that the electrons are confined within the lowest Landau level for fields greater than 0.95 kOe, and are fully spin polarized at fields above 1.4 kOe. These two fields are marked by arrows in the inset of Fig. 1, which shows the field dependence of the resistivity ρ_{xx} (H is applied in the z direction). Corresponding to the arrows we see two weak Shubnikov–de Haas oscillations which demonstrates that the system is already in the extreme quantum limit by $H=2$ kOe.

The H dependence of ρ_{xy} is shown for $0<H<18$

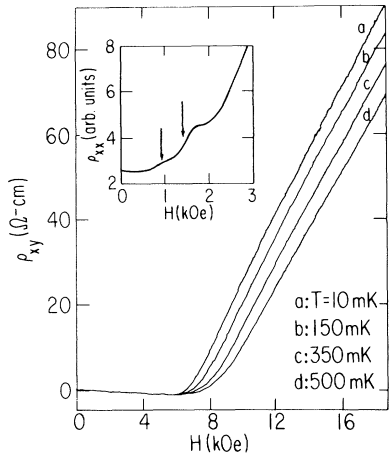

FIG. 1. The resistivity ρ_{xx} and Hall resistivity ρ_{xy} as a function of magnetic field H along z. The arrows in the inset mark Shubinkov–de Haas oscillations (see text), with the system reaching the extreme quantum limit by 2 kOe. The parallel behavior of $\rho_{xy}(H)$ at different temperatures T indicates a collective effect, with the actual T dependence illustrating the critical form.

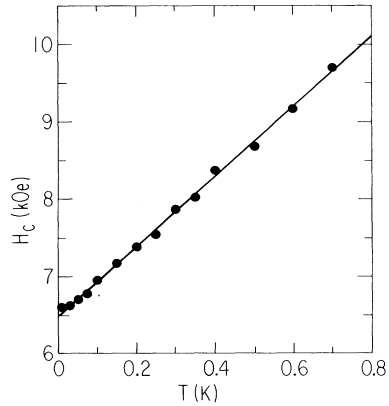

FIG. 2. The linear dependence of the critical field H_c on temperature as determined by extrapolation of ρ_{xy} to zero. This form suggests a Wigner crystal.

kOe in the main body of Fig. 1. At a critical field H_c, which is a strong function of T, there is a sharp rise in ρ_{xy}. The rise continues smoothly to the highest field measured, $H=75$ kOe, switching from a slightly sublinear to a slightly superlinear H dependence at approximately 40 kOe. An abrupt rise is also seen in ρ_{xx} and ρ_{zz} at the same field H_c.

A sudden rise in ρ_{xx} and ρ_{xy} as a function of increasing field has in fact been observed previously but at higher temperatures, and its explanation has been a source of some controversy. The temperature dependence of H_c which we observe at these low temperatures (Fig. 2) has not been seen before, and this allows us to discern the appropriate physics. First we discuss the energy and length scales appropriate for this problem.

With the electrons confined to the lowest spin-polarized level, there is dispersion only in the z direction, and the Fermi wave vector $k_F=2\pi^2 nl^2$ is set by the magnetic length $l=(\hbar c/eH)^{1/2}$. For the parameters of our sample this leads to a Fermi temperature $T_F=\hbar^2 k_F^2/2m^* k_B=10/H^2$ K, with the field H measured in kilo-oersteds. The energy scale for Coulomb interactions of electrons with charged impurities is set by the effective Rydberg $k_B T^*=\hbar^2/2m^* a^{*2}$, where $a^*=\epsilon_\infty(m/m^*)a_0$ is the effective Bohr radius; here we have $T^*\sim 4$ K and $a^*\sim 900$ Å. Since we have $n^{1/3}a^*\simeq 0.5$, the Coulomb interaction *between* electrons is on a comparable energy scale to $k_B T^*$. Consequently $T^*/T_F \gtrsim 1$, and the system is in the strong-coupling limit where the interaction strength is larger than the bandwidth; furthermore for $H\gtrsim 3$ kOe, $T_F<1$ K and the system becomes nondegenerate at our measuring temperatures.

The carrier density is low enough that we should expect to be close to a metal-insulator transition at zero field, although this sample was still a good metal at zero field and at 100 mK, with a conductivity of 5.3 $(\Omega\ \text{cm})^{-1}$, several times greater than the characteristic scale of conductivity $\sigma_0=0.025e^2 n^{1/3}/\hbar=0.3$ $(\Omega\ \text{cm})^{-1}$ near a zero-field metal-insulator transition. As the field is increased into the extreme quantum limit the size of an electron wave packet shrinks in the direction transverse to the field; for $H>1$ kOe, we have $l<a^*$.

We can rule out magnetic freezeout as a plausible explanation for the behavior shown in Fig. 1. If individual electrons were condensing onto isolated donors,[8] then one expects $n\propto T^{1/2}\exp(-\Delta/T)$ at field H, where $\Delta(H)$ is the donor binding energy. This is clearly not in agreement with our data because the curves for ρ_{xy} are parallel at different temperatures, unlike the case of InSb where an activated behavior has been seen.[10] Freezeout onto isolated donors cannot occur if the donor level is resonant with the conduction band, as may be the case[8] in HgCdTe. Even for shallow donors we expect simple freezeout to be unlikely because it requires the carriers to localize in the weak Coulomb tails of the donor potential where disorder must dominate. An "Anderson" transition driven by increasing effective disorder is also implausible because there would be one H_c, independent of T, except for possible thermal smearing. In fact $d\rho_{xy}/dH$ is approximately independent of T above H_c, and the rounding near H_c is only weakly dependent on T and therefore apparently due to inhomogeneities rather than thermal effects. If previous experiments on doped semiconductors[12] serve as a guide, we would not expect to see the effects of a $T=0$ metal-insulator transition until $T\lesssim 10^{-4}T^*\simeq 0.5$ mK. Because the size of an electron wave packet is so large, the carriers

average very effectively over a random potential on length scales $< l$, and the effects of disorder are rather weak. This also accounts for the high mobilities that we observe.

We believe that the physics is dominated by Coulomb effects, and that H_c signals the onset of a Mott transition produced by electron correlation, most likely into a charge-density-wave (CDW) or Wigner crystalline state. This would be expected to lead to a field-dependent critical temperature, and in Fig. 2 we plot H_c as a function of T, where H_c has been determined by linearly extrapolating $\rho_{xy}(H)$ to zero. The solid line is a least-squares fit $H_c = 6.5 + 4.5T$, where T is in kelvins and H in kilo-oersteds. In Fig. 3, we demonstrate that the behavior is three dimensional, by comparing the critical behavior of the conductivity perpendicular (σ_{xx}) and parallel (σ_{zz}) to H. The solid lines are nonlinear least-squares fits to $\sigma = A(H - H_c)^{\alpha}$, with the exponent α indicated. The values of of H_c are the same to within 8% and agree within experimental error to that obtained from ρ_{xy} in Fig. 2, while the prefactors differ by a factor of 2.

The linear dependence of H_c on T_c differs from the BCS-like dependence $T_c = 1.14 T_F \exp[-(\pi/\phi_0)(T_F/T^*)^{1/2}]$ (here ϕ_0 is a number of order unity, weakly dependent on H) suggested by Fukuyama[13] for the phase boundary of a continuous CDW transition, and in good agreement with experiments on graphite at very high fields.[3] However, these calculations were performed in the weak-coupling limit $T^*/T_F \ll 1$, which is not appropriate here. In the strong-coupling limit a much weaker than exponential dependence is expected,[13] and Gerhardts[14] finds $T_c = (4\phi_0/\pi) \times (T_F/T^*)^{1/2}$ for a continuous CDW transition, giving

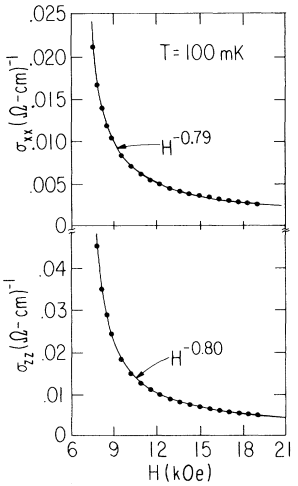

FIG. 3. The conductivity perpendicular (σ_{xx}) and parallel (σ_{zz}) to H. The lines are nonlinear least-squares fits to $\sigma = A(H - H_c)^{\alpha}$. The same α and H_c for the two directions reflect the three-dimensional nature of the transition.

T_c *decreasing* as $1/H_c$ at high fields, which is also inconsistent with our data. The assumption of a continuous CDW transition is suspect in this system,[14,15] given that $T_F/T_c \sim 1$. A better starting point is probably to consider the melting transition of a Wigner crystal, which is likely to be first order.

Calculations by Kleppmann and Elliott[16] for the zero-temperature critical field needed to induce a Wigner transition give $H_c \sim 3$ to 4 kOe for the parameters of our system; this is close to the value that one would predict from taking $n^{1/3}l \simeq 0.2$ for a Mott insulator, and is within a factor of 2 of our data at $T = 0$. Although no calculations for finite temperature exist, if we estimate[16] the melting temperature to be $\frac{1}{8}$ the cohesive energy per electron, we obtain $dT_c/dH = 0.3$ K/kOe, for $H_c(T = 0) = 6.5$ kOe, very close to the experimental value of 0.22 K/kOe. At very high fields, the cohesive energy of the Wigner lattice should tend to a constant[1] given by $1.79 k_B T^*/r_S$, where $4\pi r_S^3 = 1/na^{*3}$; in our system this would lead to a saturation of T_c at about 1 K in high fields. The factor of 2 in the conductivity ratio σ_{zz}/σ_{xx} is also consistent with the estimates of Kleppmann and Elliott.[16]

A brief summary of our picture is as follows. For *any* temperature $T < \hbar\omega_c/k_B$, we expect that there will be a sharp crossover from delocalized electronic states to a highly correlated electron "fluid" at a typical field such that $n^{1/3}l \sim 0.2$; at low temperatures $T \sim 0.2T^*/r_S$ reached in this experiment, the electrons crystallize into a Wigner solid. The important assumption here is that disorder is relatively unimportant because of the large size of the electron wave packets (in contrast with, for example, the behavior in GaAs where $a^* \sim 75$ Å).[17] However, even weak disorder will be sufficient to pin the electron lattice to the crystal[18] by introducing fluctuations on a length scale $\gg n^{-1/3}$. The pinning of the lattice should lead to nonlinear I-V characteristics at sufficiently high currents.[6] The most direct and accessible experimental test of this picture (given the difficulties of studying such a low carrier density) would be a tunneling measurement of the density of states where we expect to see the opening up of a gap at the critical field H_c.

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Note added.—Experimental work on higher density n-type HgCdTe by Shayegan *et al.*[19] was called to our attention after this Letter was submitted. Their results at higher temperature and field are consistent with ours, but have been interpreted differently.

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